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ELECTRONS FROM BOMB NEUTRON DECAY

Killeen, Hess and Lingenfelter

INTRODUCTION

The purpose of this paper is to calculate the trapped electron flux resulting from the decay of neutrons emanating from a point source. The best example of such a source is a nuclear explosion above the earth's atmosphere. Neutrons going out radially from the explosion decay by the reaction

$$n \rightarrow p + e + \bar{\nu}$$

with a mean life τ of 1000 seconds. The electrons resulting from the neutron decay have an energy spectrum nearly independent of the neutron velocity (Nakada, 1963).

There have recently been several high altitude nuclear explosions that are essentially point sources of neutrons. It is of interest to evaluate the additions to the radiation belt resulting from neutron decay. It is known that some energetic particles were observed at large distances from the Starfish explosion of July 9, 1962. Ariel observed particles up to L = 6 (Durney, Elliot, Hynds and Quenby, 1962). We will consider here sources both off and on the magnetic equator and study neutrons directly from the source and also albedo from the top of the atmosphere.

An Equatorial Source

Starting with a neutron source on the magnetic equator the total flux F of neutrons passing through 1 cm^2 area at a point in space at a distance ρ from the source is

$$F = \frac{M}{4\pi\rho^2}$$

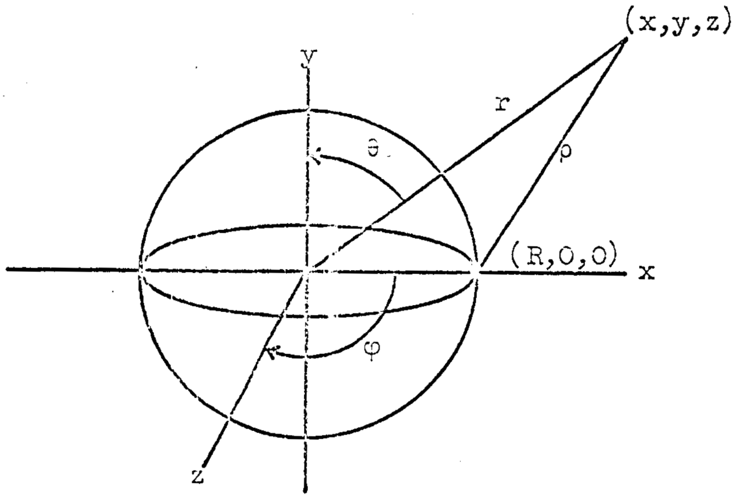
where M is the total number of neutrons from the source. This neglects neutron albedo from the atmosphere which will be considered later. The number of neutron decays per cm^3 at this point is

$$n_o = \frac{M}{4\pi\rho^2 v\tau} \qquad (1)$$

where v is the neutron velocity. Evaluating from Figure 1,

$$\rho^2 = (x - R)^2 + y^2 + z^2 \qquad (2)$$

Figure 1:



where

$$x = r \sin\theta \cos\varphi$$
$$y = r \cos\theta \cos\varphi \qquad (3)$$
$$z = r \sin\varphi$$

substituting gives

$$\rho^2 = r^2 + R^2 = 2rR \sin\theta \cos\varphi \qquad (4)$$

Let $s = r/R$ and $\alpha = \rho/R$, then

$$n_0(s,\theta,\varphi) = \frac{M}{4\pi v\tau R^2\alpha^2} = \frac{M}{4\pi v\tau R^2}\left(\frac{1}{\sqrt{1+s^2-2s\sin\theta\cos\varphi}}\right)^2 \qquad (5)$$

The equation of a field line is

$$\frac{\sin^2\theta_0}{R} = \frac{\sin^2\theta}{r} \qquad (6)$$

where θ_0 is the magnetic colatitude of the line at the earth's surface. Along a field line we have

$$s = \frac{\sin^2\theta}{\sin^2\theta_0} \qquad (7)$$

The neutron decay density given in (5) is also the electron source density. Integrating equation (5) over longitude we get

$$\bar{n}_0(r,\theta) = \frac{1}{\pi}\int_{-\varphi_0}^{+\varphi_0} n_0(r,\theta,\varphi)\,d\varphi = \frac{M}{2\pi^2 v\tau R^2}\int_0^{\varphi_0}\frac{d\varphi}{1+s^2-2s\sin\theta\cos\varphi} \qquad (8)$$

This represents the electron source strength after the electrons have had time to spread out in longitude. The value of φ_0 can be found from the fact that we consider only $x > R$, or, $r\sin\theta\cos\varphi_0 > R$; this gives

$$\varphi_0 = \arccos\left[\frac{1}{s\sin\theta}\right] \qquad (9)$$

Equation (8) can be integrated directly to give

$$\bar{n}_0(s,\theta) = \frac{M}{\pi^2 v\tau R^2}\left[\frac{1}{\sqrt{1+s^4+2s^2\cos 2\theta}}\ \arctan\left\{\frac{\sqrt{1+s^4+2s^2\cos 2\theta}}{1+s^2-2s\sin\theta}\sqrt{\frac{s\sin\theta-1}{s\sin\theta+1}}\right\}\right] \qquad (10)$$

This has been evaluated to give Figure 2, using

$$k = \frac{M}{\pi^2 v\tau R^2} = 1.$$

This gives the density distribution of electrons produced along different field lines. Assuming that the electrons are emitted isotropically, we can calculate W the distribution of mirror points of the electrons

$$W(\theta_o,\theta) = \frac{1}{2}\frac{dB}{dl}\frac{1}{B(\theta_o,\theta)}\int_{\pi/2}^{\theta}\frac{n_o(\theta_o,\theta')dl'}{\sqrt{1-B(\theta_o,\theta')/B(\theta_o,\theta)}} \tag{11}$$

and from this we can get the distribution of electron flux along a field line N by

$$N(\theta_o,\theta) = B(\theta_o,\theta)\int_{\theta}^{\theta_o}\frac{W(\theta_o,\theta_t)\ dl_t}{B(\theta_o,\theta_t)vT(\theta_o,\theta_t)\sqrt{1-B(\theta_o,\theta)/B(\theta_o,\theta_t)}} \tag{12}$$

These expressions for W and N are developed in Hess and Killeen, (1961). They have been evaluated numerically to give Figures 3 and 4.

Albedo Neutrons

For a source of neutrons above the atmosphere we must consider not only neutrons coming upwards from the source but also albedo from the top of the atmosphere. Neutrons initially directed downwards into the atmosphere from the explosion site will suffer collisions in the upper atmosphere and a majority of the neutrons will be scattered back out of the atmosphere. The intensity and energy spectrum of this albedo flux have been calculated from multi-groups diffusion theory, described in detail by Hess, Canfield, and Lingenfelter, (1961).

The neutrons are assumed to come from an isotropic point source above the atmosphere, and separate calculations are made for neutrons with both a Maxwellian energy distribution at a temperature of 1 kev and a fission neutron energy spectrum. It is also assumed that the neutrons scatter isotropically at their first collision and that the density of first collisions decreases with altitude in the form $e^{-x/L\mu}$, where x is the depth beneath the top of the atmosphere in gm/cm^2, L is the collision mean free path (equal to about 4 cm^2/gm for 1 kev neutrons and about 12 cm^2/gm for fission neutrons), and μ is the cosine of the angle of incidence at the top of the atmosphere.

For normally incident neutrons the albedo, or fraction of neutrons reflected, was calculated to be 0.74 for 1 kev neutrons and 0.63 for fission neutrons. Both values increase to unity with decreasing angle of incidence, as is shown in Figure 5. Integration of these two functions over μ gives a total albedo of 0.80 for neutrons with a Maxwellian distribution at 1 kev, leaving the explosion site in the downward hemisphere, and 0.73 for similar neutrons with a fission spectrum.

The calculated energy spectra of the albedo fluxes from 1 kev and fission neutrons are shown in Figure 6, where they are compared with the incident spectra. Since diffusion theory is not rigorous within a couple of mean free paths of a boundary, the albedos thus calculated should probably have an uncertainty of about ±20%.

It is necessary to consider the neutron decay more completely in studying the albedo neutrons in the eV energy range. In this case the neutron decay density at a distance ρ from the source is

$$n_o = \frac{M}{4\pi\rho^2 v\tau} e^{-\frac{\rho}{v\tau}} \tag{13}$$

This considers neutron decay between source and observer. The integration over φ is given by

$$\bar{n}_o (s,\theta) = \frac{M}{2\pi^2 v\tau R^2} \int_o^{\varphi_o} \frac{e^{-\frac{R\alpha}{v\tau}} d\varphi}{1 + s^2 - 2s \sin\theta\cos\varphi} \tag{14}$$

This has been evaluated for values of

$$\frac{R}{v\tau} = \frac{6.4 \times 10^8}{1.45\times10^6 \sqrt{E_{ev}} \times 1000} = \frac{.44}{\sqrt{E_{ev}}} = 1,\ .5,\ .2,\ .05$$

These decay densities, n, have been transformed to electron flux distributions, N, in the same manner as before. Values of N are plotted for the four values of $R/v\tau$ in Figure 7 - 10 for $M/\pi^2R^3 = 1$.

We can now apply this analysis to a specific case. The July 9 Starfish explosion was about 1.4 MT. This released the order of 10^{26} neutrons. It was near enough the equator so the current analysis is reasonable. Let us assume that 10% of these neutrons were thermalized in the bomb debris to a temperature of 1 kev or $v = .45\times10^8 \frac{cm}{sec}$ This may not be a good assumption, but we will use it for lack of better information.

Using the neutron energy spectrum in Figure 6 a and b we can evaluate the normalizing constant K. To do this we break the neutron energy spectrum down into five energy groups that are appropriate to the five values of $R/v\tau$.

$R/v\tau$	E	energy range	f
0	∞	310 ev $\rightarrow \infty$	1.56
.05	77 ev	31 - 310 ev	.17
.2	4.8 ev	3.1 - 31 ev	5.4×10^{-2}
.5	0.8 ev	.31 - 3.1 ev	1.6×10^{-2}
1.0	0.2 ev	0 - .31 ev	8.3×10^{-3}

Now we evaluate five normalizing constants

$$k_i = \frac{M}{\pi^2 R^2} \quad \frac{f_i}{v_i \tau}$$

where fi is the fraction of neutrons in the appropriate energy range given in the Table above (totaling 1.80 due to the albedo). By using these values of k to normalize the fluxes in Figures 7 - 10, and then adding the results give the fluxes shown in Figure 11. This data in Figure 11 is the electron flux expected from Starfish with and without albedo neutrons. It has been calculated for 10% of the neutrons released appearing at 1 kev. This is only the injection flux and the lower altitude flux will decrease fairly rapidly as a result of coulomb scattering in the atmosphere. Calculations based on 100% of the released neutrons having a fission spectrum give quite similar results because the higher total flux is offset by the smaller frostion decaying.

Off Equator Sources

The Soviets have recently exploded high altitude explosions in Siberia. In order to calculate the trapped electron distribution resulting from neutron decay from such a source we can generalize the earlier expressions. Taking a source at colatitude η of coordinates $(R \sin\eta, R \cos\eta, 0)$ and a point of observation at (x,y,z) as before, we can calculate the source-observer distance ρ by

$$\rho^2 = (x - R \sin\eta) + (y \pm R \cos\eta)^2 + z^2 \tag{15}$$

The ± signs here depend on whether the point of observation is in the Northern Hemisphere (-) or the Southern Hemisphere (+).

Using this gives a neutron decay density of

$$n_o = \frac{M}{4\pi v\tau R^2}\left[\frac{1}{1+s^2-2s \sin\theta \cos\varphi \sin\eta \pm 2s \cos\theta \cos\varphi \cos\eta}\right] \tag{16}$$

This is integrable as before to give

$$\bar{n}_o(s,\theta,\eta) = \frac{M}{4\pi^2 v\tau R^2}\int_{-\varphi_o}^{+\varphi_o} \frac{d\varphi}{a+b \cos\varphi} \tag{17}$$

The integral is broken into two parts, the Northern Hemisphere ($+\varphi_o$ to 0) and the Southern Hemisphere (0 to $-\varphi_o$) and gives

$$\int_0^{\varphi_o} \frac{d\varphi}{a+b \cos\varphi} = \frac{2}{\sqrt{a^2 - b^2}} \text{ arc tan}\left[\frac{\sqrt{a^2 - b^2}}{a + b} \tan \frac{\varphi_o}{2}\right] \tag{18}$$

where $a = 1 + s^2$

$b = -2s \sin\theta \sin\eta \pm 2s \cos\theta \cos\eta$

and φ_o can be evaluated from the fact that neutrons only appear on the side of the earth where the source exists. In the region where the source exists

$$x > R \sin\eta + R \frac{\cos^2\eta}{\sin\eta} - y \cot\eta \tag{19}$$

substituting for x and y gives the limit

$$\cos\varphi_o = \frac{1}{s[\sin\theta \sin\eta \pm \cos\theta \cos\eta]} \tag{20}$$

Here the + sign is for the Northern Hemisphere.

FIGURE CAPTIONS

Hess, Killeen, Lingenfelter

1 - Coordinate system. (Figure in text)

2 - Electron source density at various points in space for several field lines of co-latitudes θ_0 resulting from decay of neutrons from a point source on the equator.

3 - Initial mirror point density of electrons at various points in space for several field lines of co-latitude θ_0 resulting from decay of neutrons from a point source on the equator.

4 - Initial electron flux distribution along several field lines of co-latitude θ_0 resulting from decay of neutrons from a point source on the equator for $k = \dfrac{M}{\pi^2 v \tau R^2} = 1$.

5 - The calculated albedo for neutrons from a point source above the atmosphere as a function of μ the cosine of the angle of incidence at the top of the atmosphere for neutrons with a Maxwellian energy distribution at 1 kev and for a fission energy spectrum.

6 - Neutron energy spectra for (a) a one kev Maxwellian source, (b) the albedo from 1 kev neutrons on the atmosphere, (c) a fission source, and (d) the albedo spectrum from fission electrons on the atmosphere.

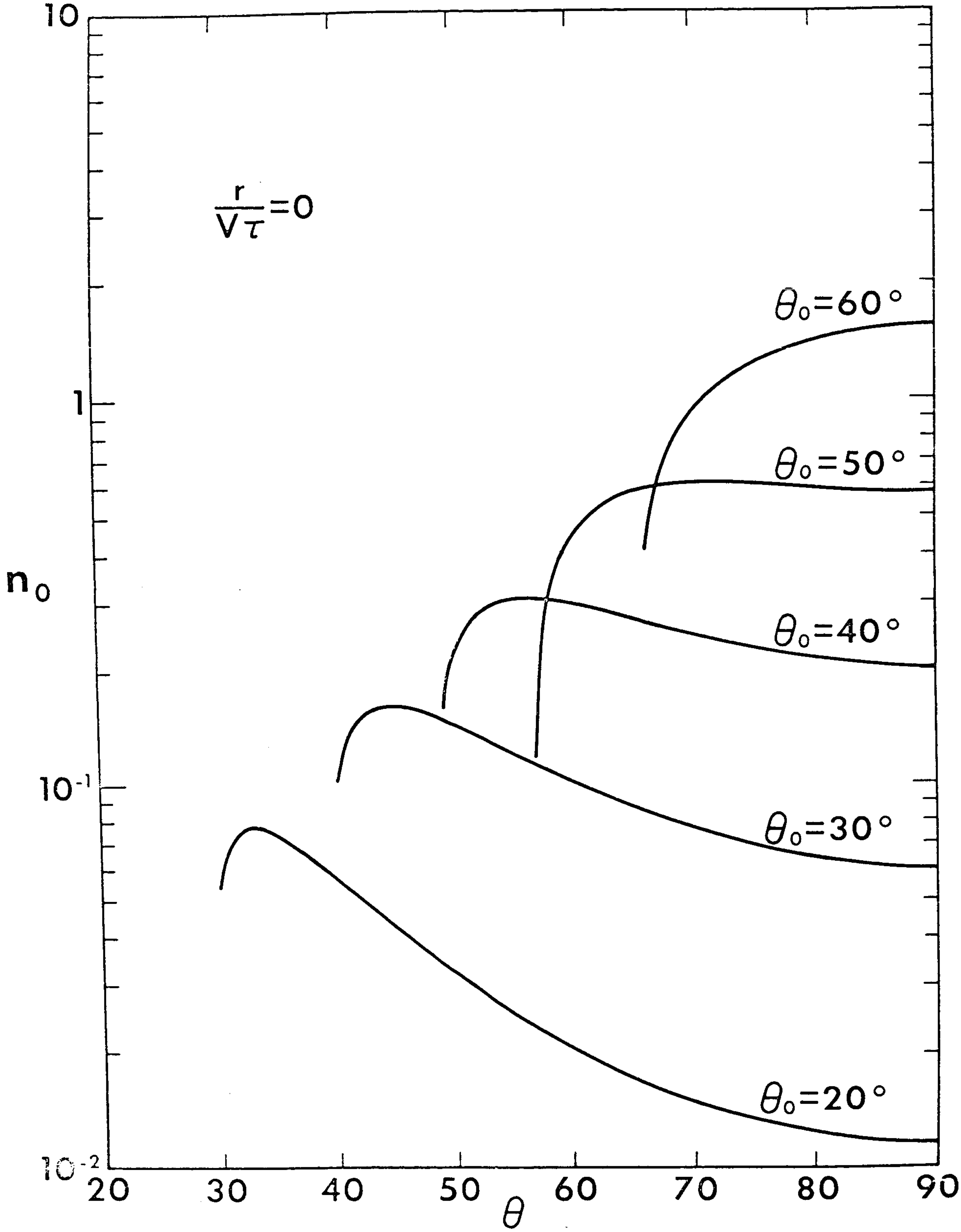
7 - Same as 4 except decay of the neutron source is considered and $\dfrac{R}{v\tau} = .05$ and $k = \dfrac{M}{\pi^2 R^3} = 1.$

8 - Same as 7 except $\dfrac{R}{v\tau} = .20.$

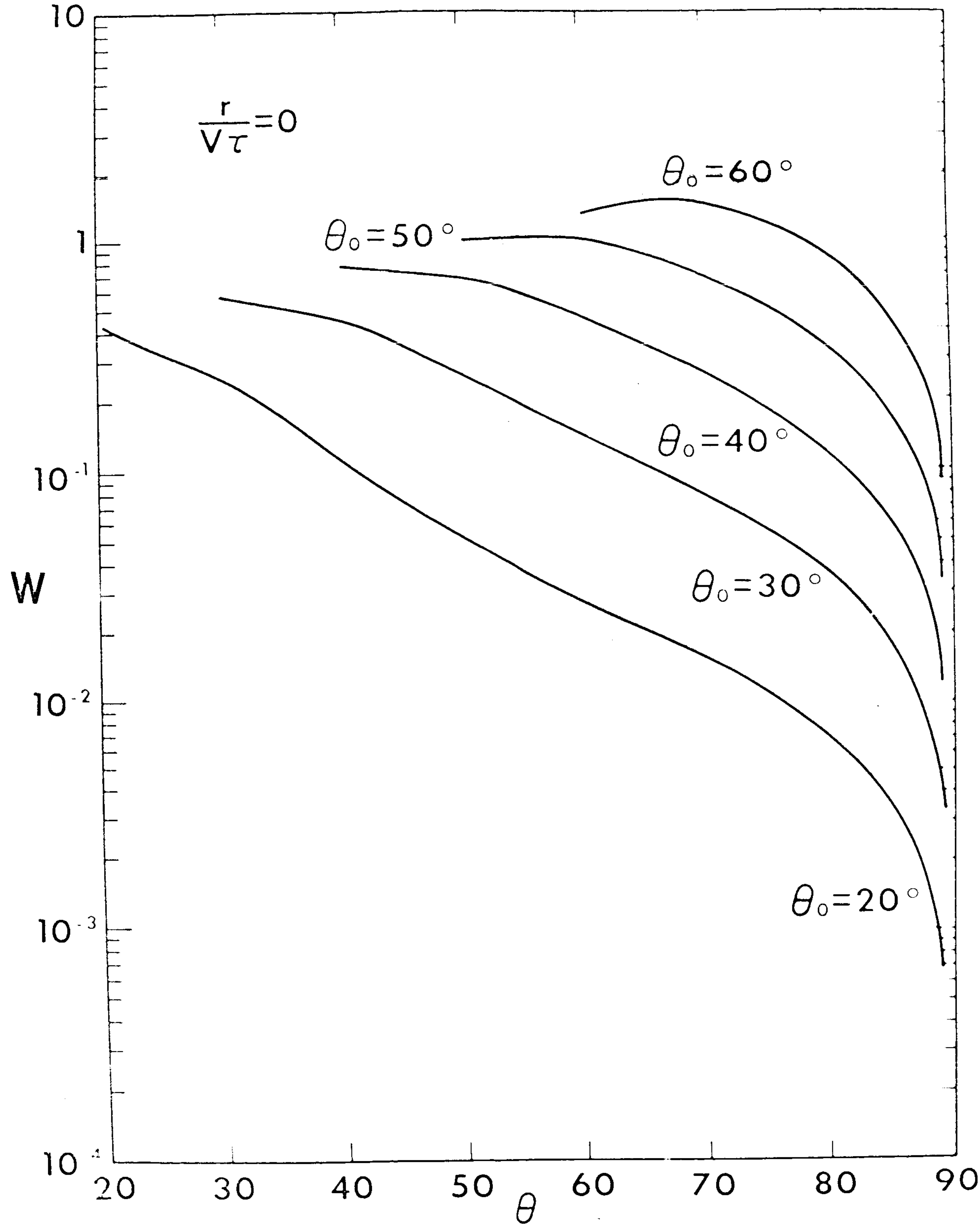
9 - Same as 7 except $\dfrac{R}{v\tau} = .50.$

10 - Same as 7 except $\dfrac{R}{v\tau} = 1.0.$

11 - Neutron decay electron fluxes expected from the Starfish explosion with and without albedo from the atmosphere.



10
1
10^{-1}
10^{-2}
n_0
$\frac{r}{V\tau}=0$
$\theta_0=60°$
$\theta_0=50°$
$\theta_0=40°$
$\theta_0=30°$
$\theta_0=20°$
20
30
40
50
60
70
80
90
θ



10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
W
$\frac{r}{V\tau}=0$
$\theta_0=60°$
$\theta_0=50°$
$\theta_0=40°$
$\theta_0=30°$
$\theta_0=20°$
20
30
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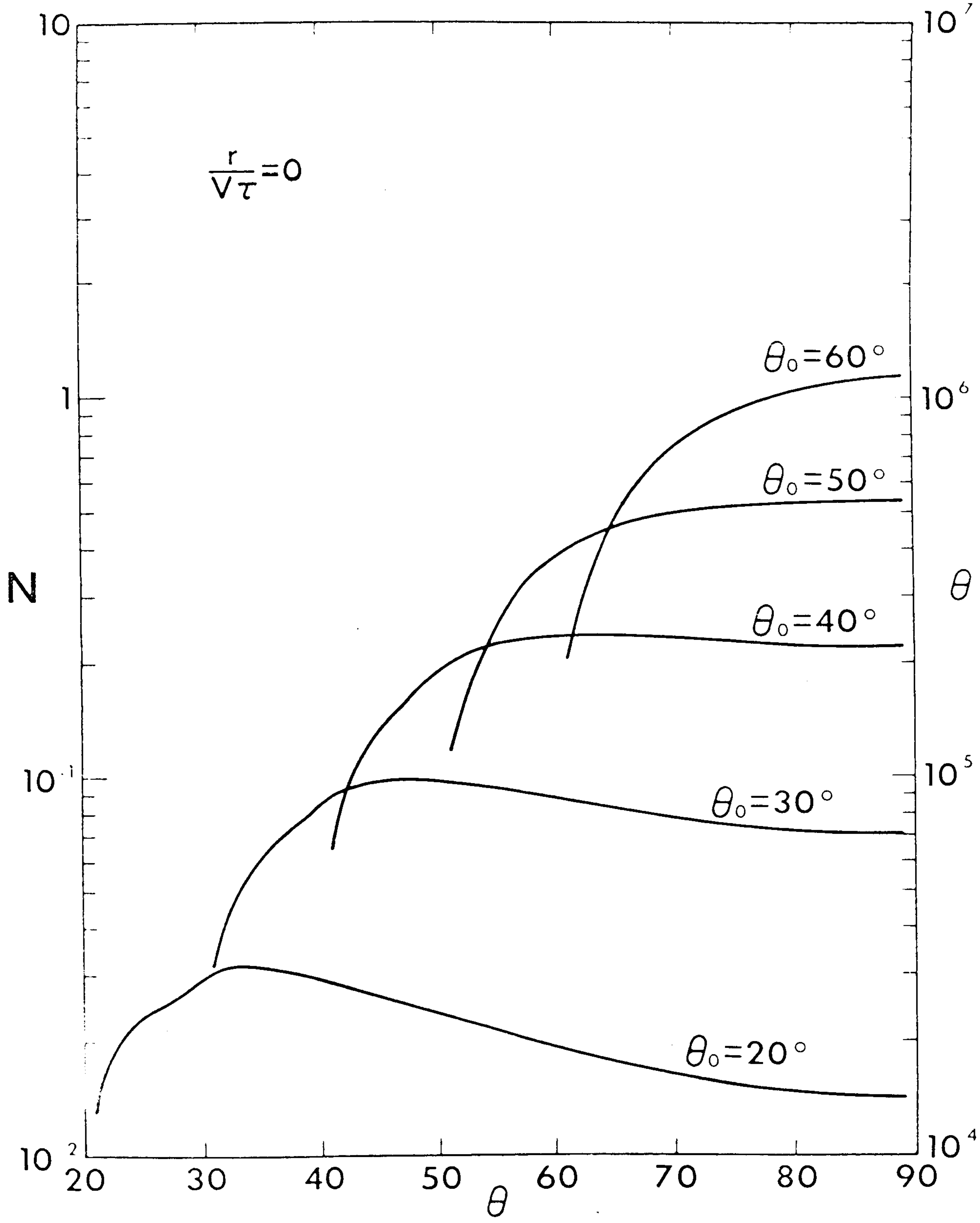
80
90
θ



$\frac{r}{V\tau}=0$
10
1
10^{-1}
10^{-2}
N
10^{7}
10^{6}
10^{5}
10^{4}
θ
$\theta_0=60°$
$\theta_0=50°$
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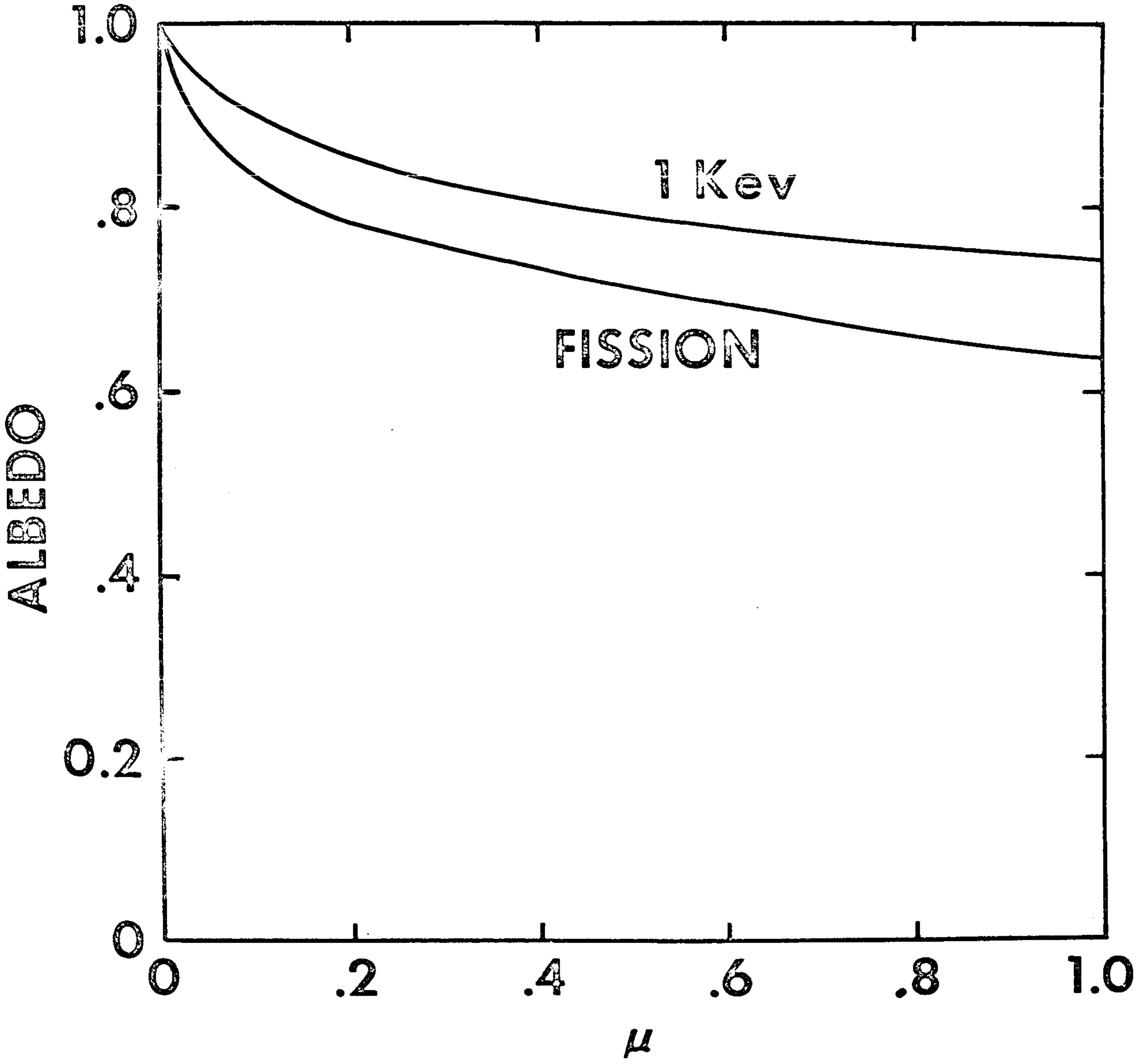
1.0
.8
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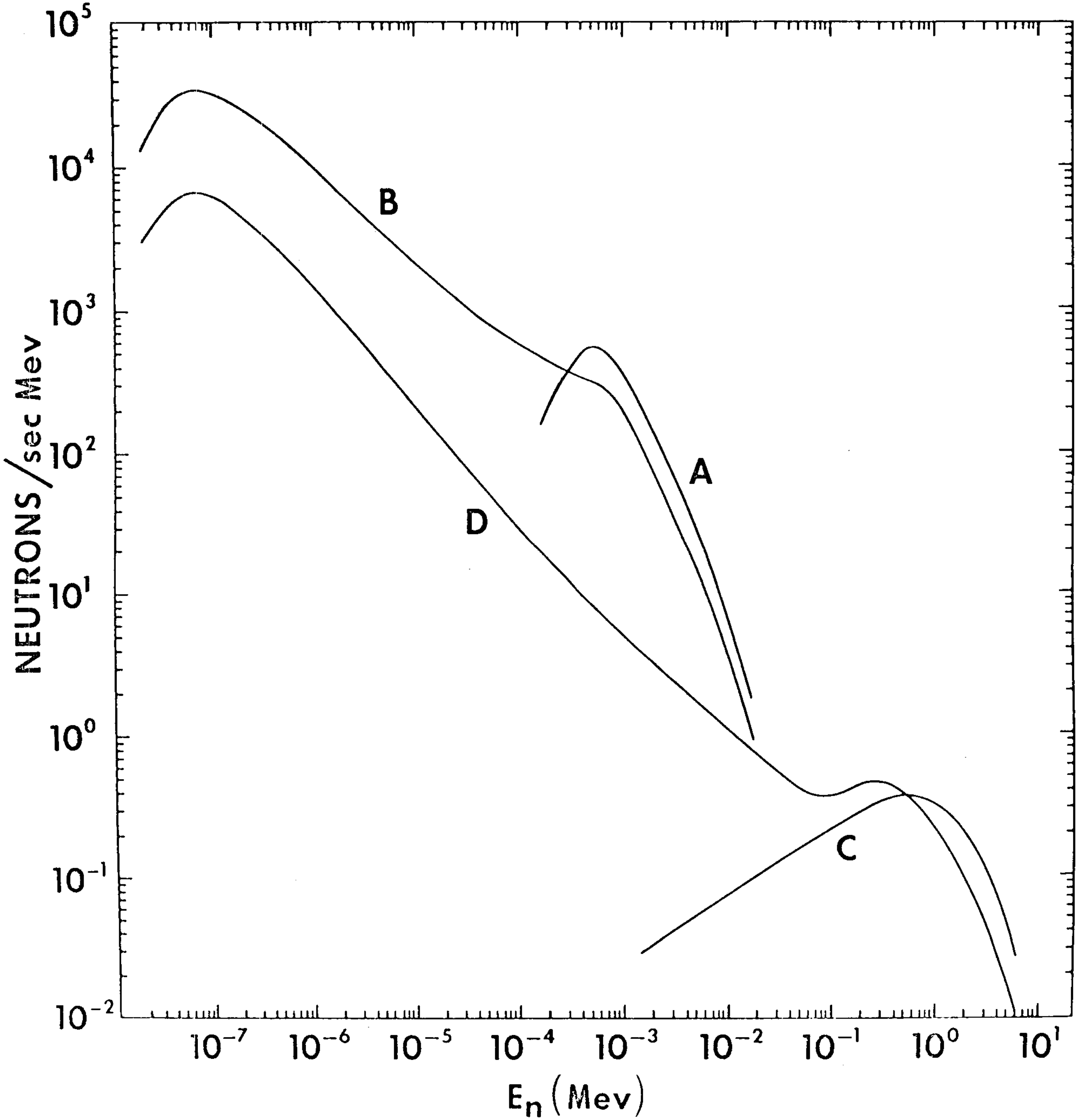
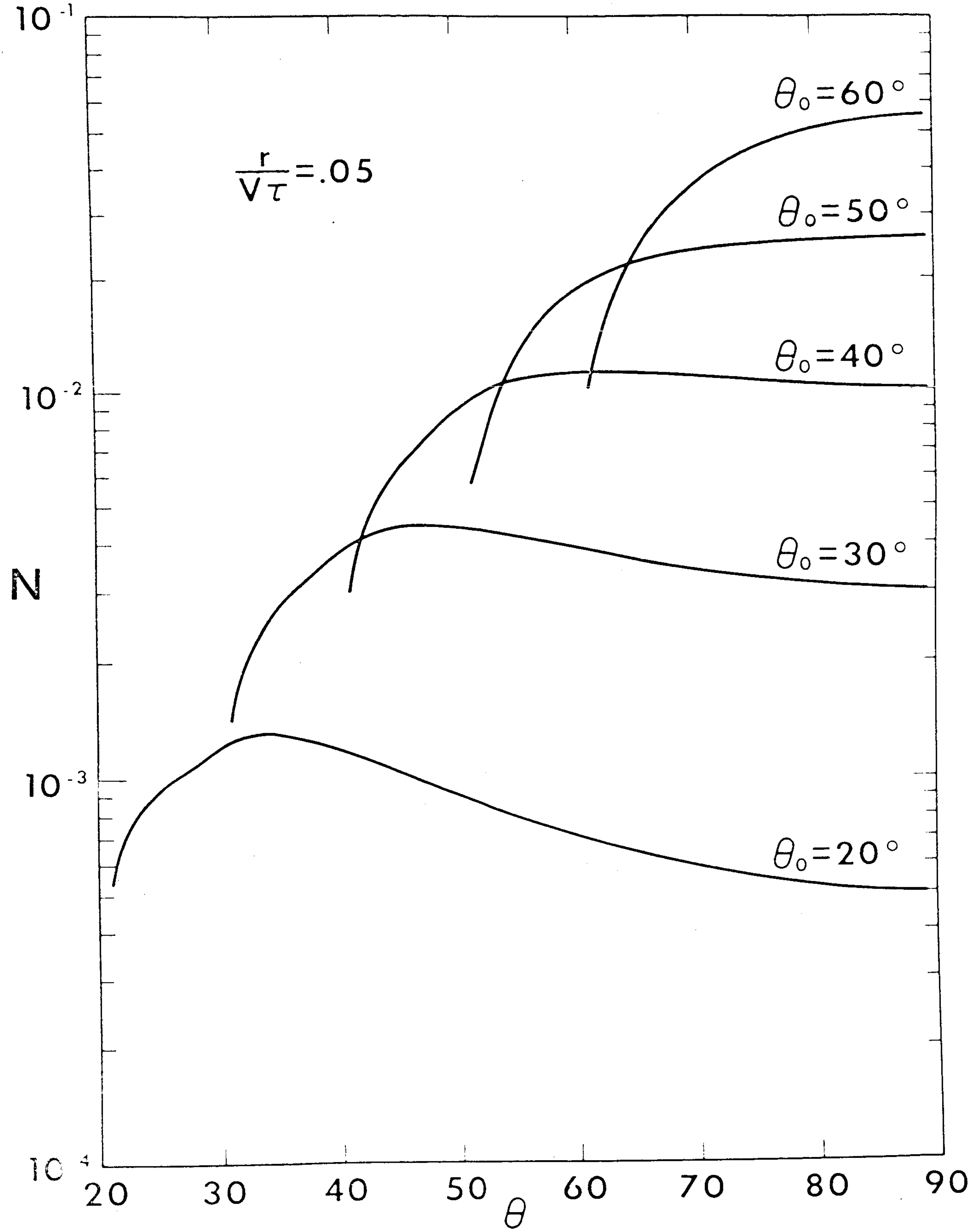
1.0
μ


NEUTRONS /sec Mev
E_n (Mev)
B
D
A
C
10^5
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
10^1



10^{-1}
10^{-2}
10^{-3}
10^{-4}
N
$\frac{r}{V\tau} = .05$
$\theta_0 = 60°$
$\theta_0 = 50°$
$\theta_0 = 40°$
$\theta_0 = 30°$
$\theta_0 = 20°$
20
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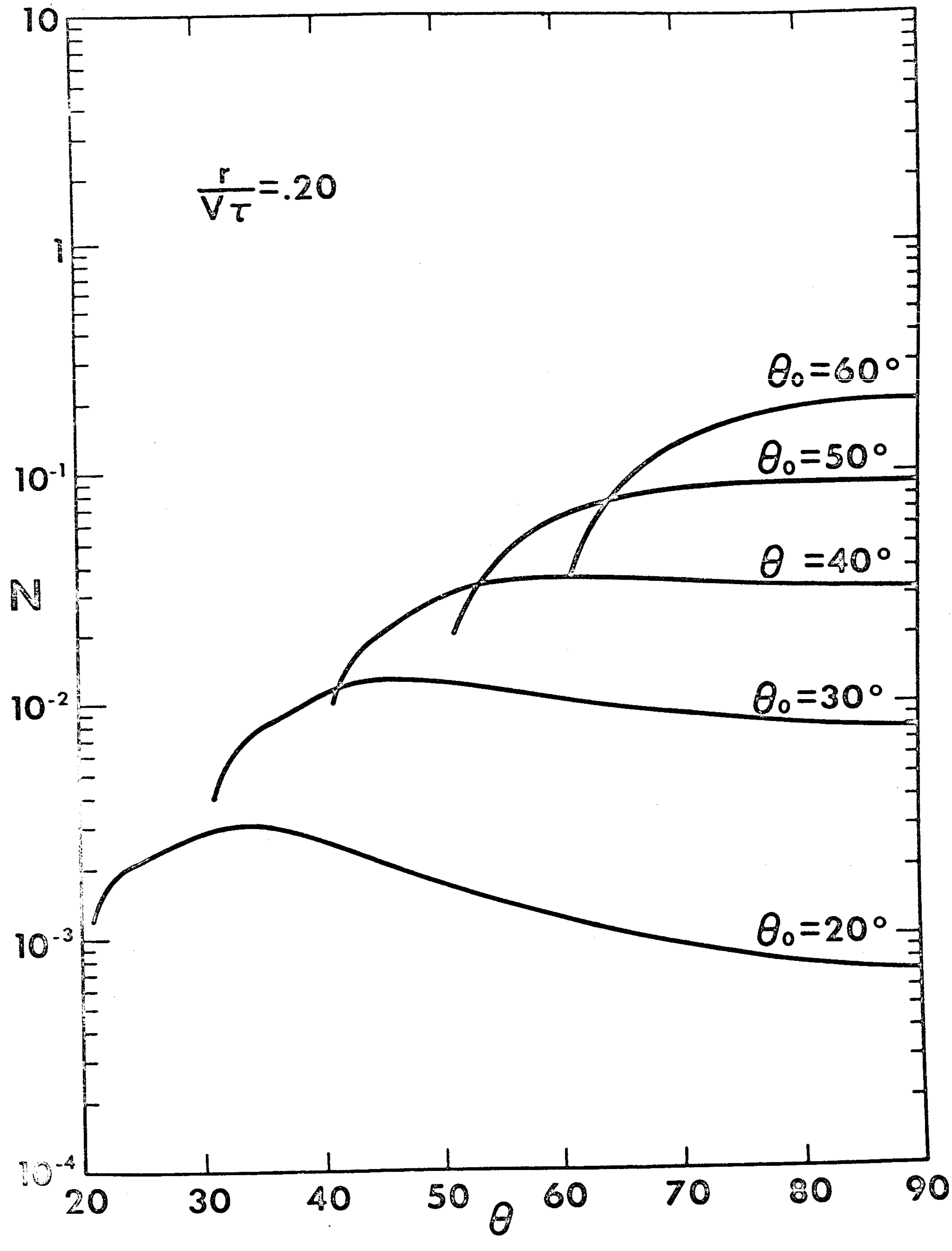

10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
N
$\frac{r}{V\tau}=.20$
$\theta_0=60°$
$\theta_0=50°$
$\theta\ =40°$
$\theta_0=30°$
$\theta_0=20°$
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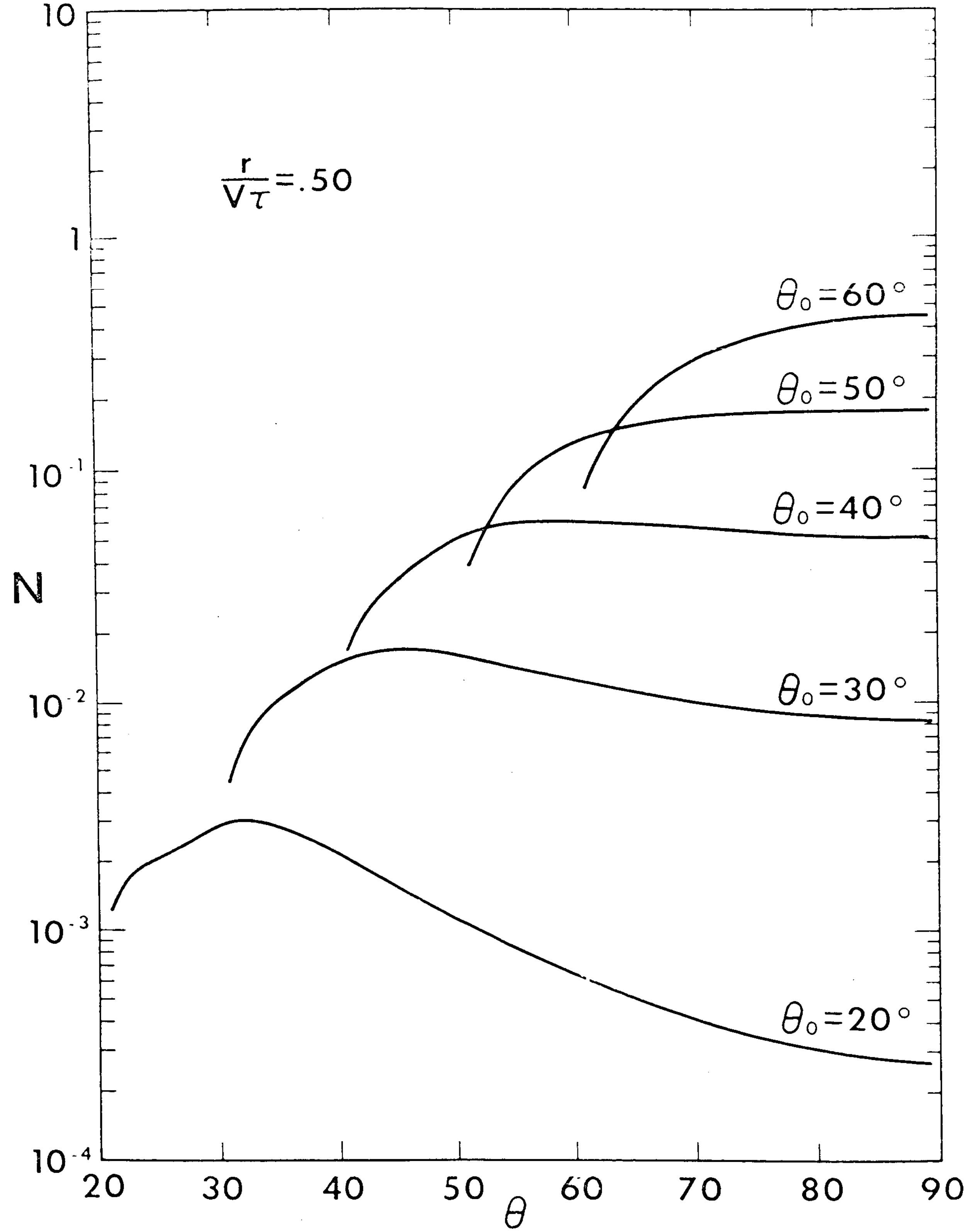

$\frac{r}{V\tau}=.50$
$\theta_0=60°$
$\theta_0=50°$
$\theta_0=40°$
$\theta_0=30°$
$\theta_0=20°$
N
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10^{-1}
10^{-2}
10^{-3}
10^{-4}
20
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40
50
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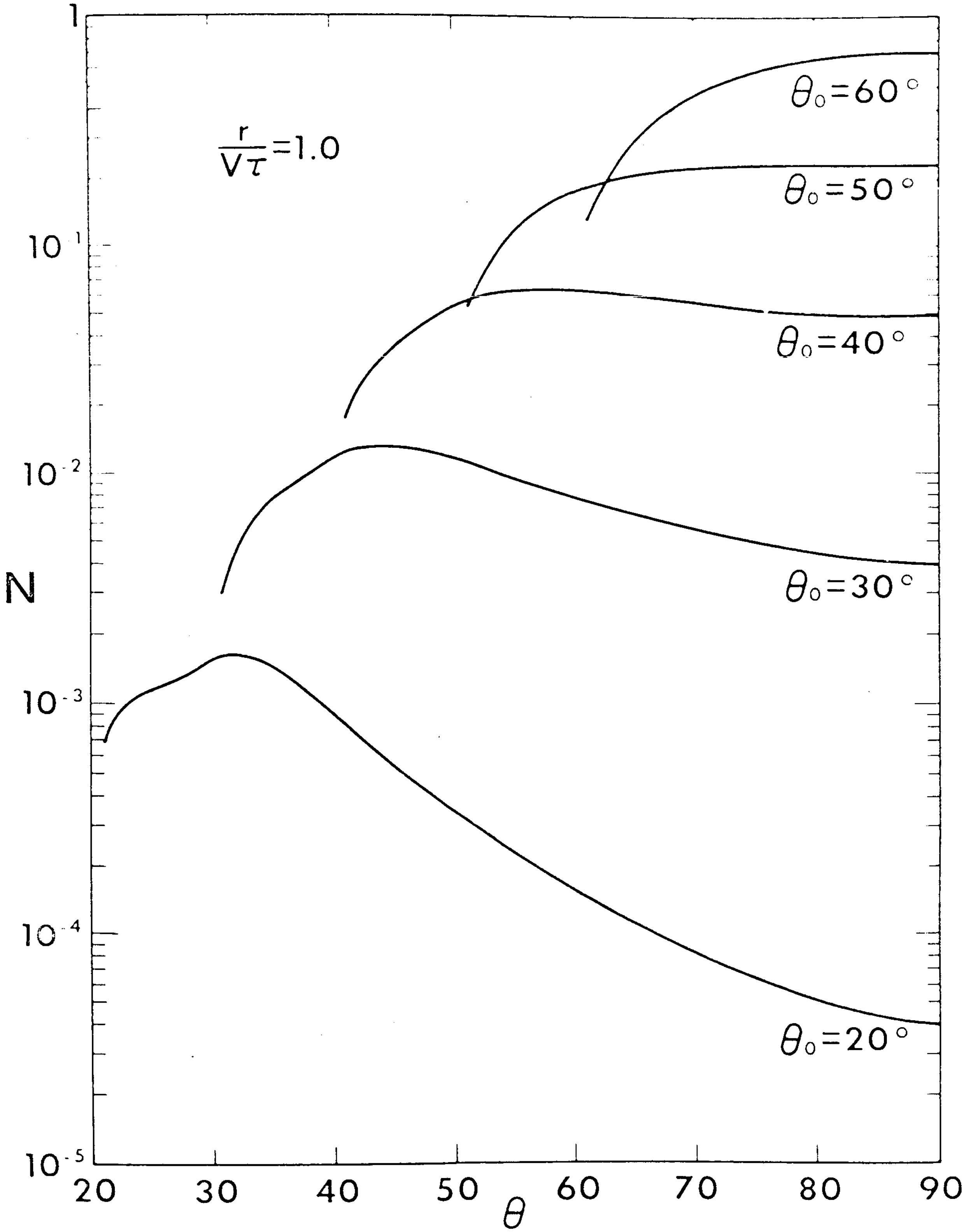
80
90



1
$\frac{r}{V\tau}=1.0$
$\theta_0=60°$
$\theta_0=50°$
10^{-1}
$\theta_0=40°$
10^{-2}
N
$\theta_0=30°$
10^{-3}
10^{-4}
$\theta_0=20°$
10^{-5}
20
30
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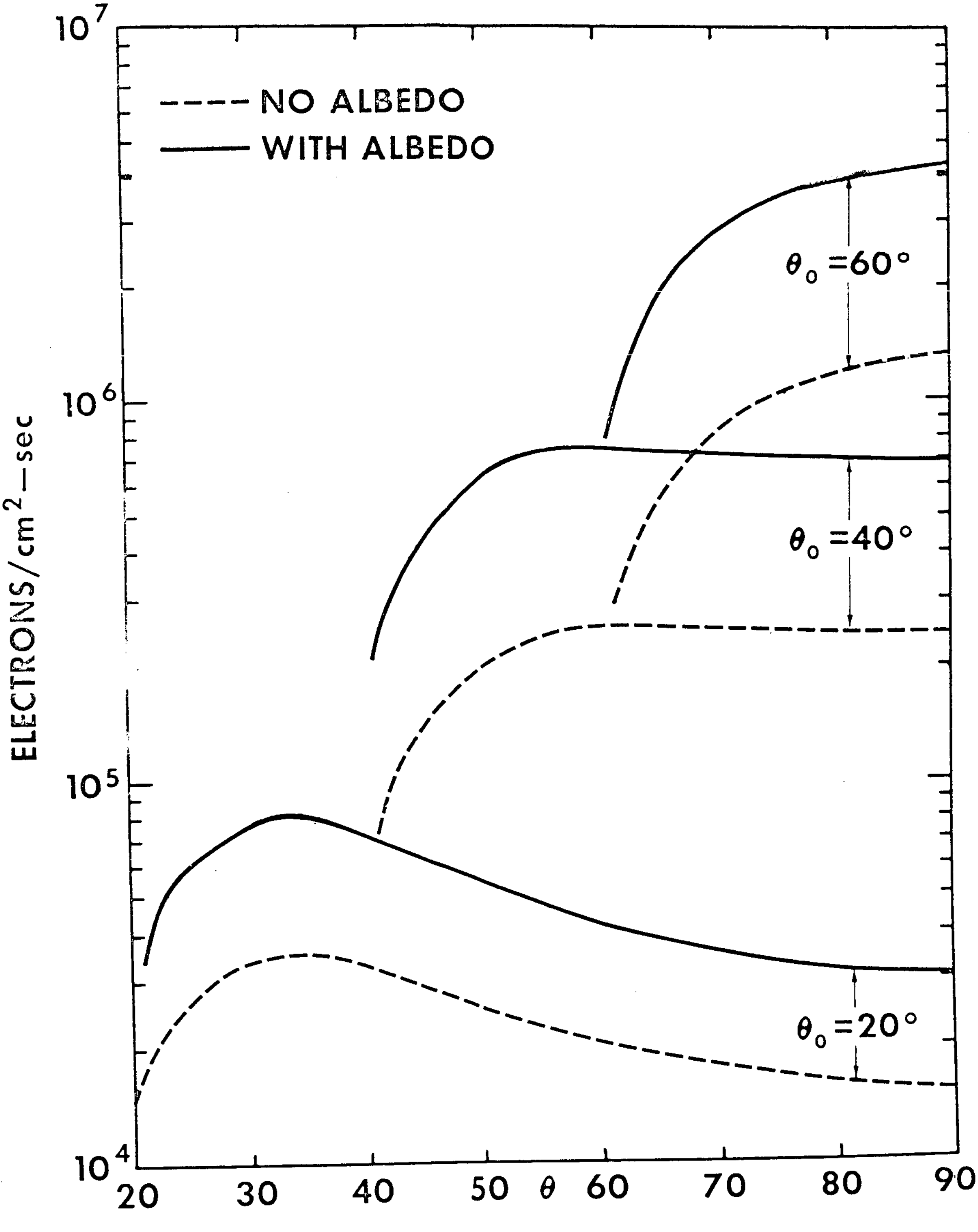
50
60
70
80
90
θ



NO ALBEDO
WITH ALBEDO
$\theta_0 = 60°$
$\theta_0 = 40°$
$\theta_0 = 20°$
ELECTRONS/cm^2—sec
10^7
10^6
10^5
10^4
20
30
40
50
θ
60
70
80
90